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2차측 제어 정유압 변속기를 이용한 풍력발전시스템에 관한 연구
A Study of Wind Energy Conversion System by a Secondary Control Hydrostatic Transmission

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Abstract: Wind energy has been more and more important and contributive in the energy utilization of the world. This paper proposed a novel method for Wind Energy Conversion System (WECS), in which a secondary control hydrostatic transmission (SC-HST) with two hydraulic accumulators, were employed for wind energy conversion system. This approach can absorb the excessive power of turbine, keep the generator from over-speed and maintain the speed of generator in low speed of turbine. A PID controller was designed for speed control to track a predefined speed. The simulation results indicated that the speed of the generator was ensured with the relative error less than 2%; and the efficiency of the proposed system was 70.4%.

NOMENCLATURE

A_v : Valve-throttling area, *squaremeter*
C_d : Discharge coefficient
D_{max} : Maximum displacement of pump
$E_{w,max}$: Maximum wind energy in one cycle
K_{sv} : DC gain of displacement control
n : Specific heat ratio
Q_b : Boost flow rate
Q_i, : Ideal flow rate of hydraulic machine
Q_{ha} : Flow rate into accumulator
Q_l : Loss flow rate of hydraulic machine
Q_{mi} : Flow rate into the inlet port of the motor
Q_{mo} : Flow rate from motor outlet port
Q_{pm} : Actual flow rate of hydraulic machine
Q_{po} : Output flow rate of the pump
$Q_{r1,2}$: Flow rate via relief valve $RV_{1,2}$
p_0 : Pre-charged pressure of hydraulic accumulator
p_i : Pressure at the port of hydraulic accumulator
p_l : Returning line pressure as pressure in LPA
T_{ex} : External torque
T_l : Loss torque of hydraulic machine
T_m : Torque of hydraulic motor
$u(t)$: Electric signal control
u_2 : Displacement ratio of pump/motor PM_2
V_0 : Volume of hydraulic accumulator
V_f : Fluid volume in the accumulator
V_h : Volume of fluid in the hose
a : Displacement ratio
β : Fluid bulk modulus
Δp : Pressure difference
t : Time constant of displacement control mechanism

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w : Hydraulic motor speed
δ : Valve throttling area proportionality coefficient

1. Introduction

Wind energy (WE) is one of the most popular renewable energy resources and it will be a promising contribution in future1)-3). So far, many researches of wind energy have been done with the aim of increasing efficiency and reducing cost4), 5). In traditional wind turbines, gearboxes or mechanical transmissions were employed to drive the generators6). One of disadvantages to wind energy conversion system is the variable speed of wind turbine causes over-speed or lack of power to drive the generator.

To prevent the over-speed of generator, some methods such as pitch control, yaw control, stall control, brake or combination of these methods were proposed as in 7)-8). Nevertheless, these methods require a complex structure of wind turbine. Some control algorithms were employed for speed control and Maximum Power Point tracking (MPPT) were proposed to drive the average position of the operating point near to optimality, as in 9)-11). However, these algorithms are rather complicate and time consuming to build. Moreover, the excessive power was waste by shedding wind flow.

In addition, the drawbacks of mechanical transmission in conventional WECS are low efficiency, premature failure and more maintenance requirement. To overcome these drawbacks, the mechanical transmission was replaced by a hydrostatic transmission (HST-WECS) as in 12)-14). HST in this application is highly efficient, less requirement of maintenance and more reliable.

However, like conventional WECS, the HST-WECS also cannot absorb the redundant power during over-speed and cannot supply enough power to drive the generator, as the turbine speed is low. To solve these problems, this study proposed a HST with two hydraulic accumulators, also known as secondary control HST, for WECS, called as'Secondary control hydrostatic transmission wind energy conversion system (SCHST-WECS). By adding the high-pressure accumulator, the operation principle of HST changes from flow coupling to pressure coupling 15), so that the redundant power during over-speed is absorbed and stored for using later, especially in low speed condition of turbine. The performance of the proposed system was verified by simulation using AMESim software.

The remains of this paper are organized as follow: section 2 describes the proposed WECS operation principle; section 3 explains the mathematical model of hydraulic system; section 4 shows the experiments and analysis of the experimental results. Finally, conclusion is presented in section 5.

2. Description of SCHST-WECS

Overview of a wind energy conversion system is shown in Fig. 1 and the hydraulic circuit of SCHST-WECS is shown in Fig. 2. The hydraulic circuit in the proposed system is a closed-loop hydrostatic transmission with two hydraulic accumulators added. Wind flow rotates the turbine to drive a high displacement pump P1. The high-pressure accumulator HPA stores hydraulic energy from pump P1 and supplies to motor PM to drive the generator. The low-pressure accumulator LPA functions as a low-pressure and high-flow source for the pump P1 to boost the hydraulic system and prevent the cavitation phenomenon at the input port of pump P1. The pressure of LPA is maintained in an interval [5-7bar] by the boost pump P2. The turbine and hydraulic pump capture energy from wind, which varies in amplitude, frequency and power. The captured energy is storied in the high-pressure accumulator. The clutch CL coaxially connects motor PM and generator G to protect the generator G from over-speed.

A PID controller was employed to control the hydraulic motor PM. The coefficients Kp, Ki and Kd were chosen with criteria of small error, small overshoot and fast response. By try and error method, coefficients of PID controller were chosen as Kp=1, Ki = 0.005 and Kd = 0.05.

An ON/OFF controller to maintain the pressure of HPA controlled the boost pump P2. The pump P2 was ON when HPA pressure was lower than 5bar and it was OFF when the pressure was higher than 7bar. A clutch placed between motor PM and generator G was controlled by an ON/OFF controller. If the generator speed exceeds the limit speed, PM and G were disconnected to protect the generator G.

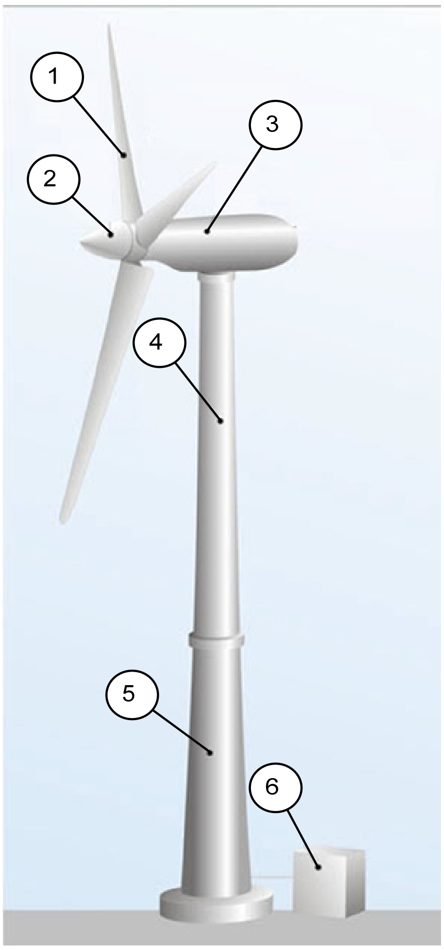


Fig. 1 Overview of a wind energy conversion system. 1-Rotor blade; 2-Rotor hub; 3-Nacelle Cover; 4-Tower; 5-Footing; 6 - Transformer.

3. Mathematical Modeling of SCHST-WECS

3.1 Model of hydraulic pump

The ideal flow rates, volumetric and mechanical efficiencies of the piston hydraulic pump are expressed in (1), (2) and (3), respectively:

$$Q_i = \alpha\omega D_{\max} \tag{1}$$

$$\eta_{vP} = (Q_i - Q_l)/Q_i \tag{2}$$

$$\eta_{tP} = (\alpha D_{\max}\Delta p)/(\alpha D_{\max}\Delta p + T_l) \tag{3}$$

The actual output flow rate and input torque of the pump are expressed in (4) and (5), respectively:

$$Q_o = Q_i\eta_{pV} \tag{4}$$

$$T_i = \alpha\Delta p D_{\max}\eta_{tPM} \tag{5}$$

where Q_i, Q_l and T_l are the ideal flow rate, loss flow rate and loss torque of the pump, respectively, discussed in 16).

3.2 Model of hydraulic motor

The volumetric efficiency, mechanical efficiency, actual flow rate and actual output torque of the piston hydraulic motor are expressed by (6)-(9), respectively.

$$\eta_{vM} = \alpha D_{\max}\omega/(\alpha D_{\max}\omega + Q_{loss}) \tag{6}$$

$$\eta_{tM} = (\alpha D_{\max}\Delta p - T_{loss})/(\alpha D_{\max}\Delta p) \tag{7}$$

$$Q_m = Q_i/\eta_{vM} \tag{8}$$

$$T_m = \alpha\Delta p D_{\max}\eta_{tM} \tag{9}$$

3.3 Electro-hydraulic displacement control mechanism (DCM)

An electro-hydraulic mechanism regulates the angle of the swash plate for control the displacement of the hydraulic machine. The full order model of the system is a fifth-order system with voltage input and the angle of the swash plate or the displacement of the hydraulic machine. However, in practical application of hydraulic systems, a reduced first-order model is often used instead of the full order model 17)-18). In this study, a first-order model of the electro-hydraulic mechanism is used and expressed as in the below equation:

$$u(t)=\tau\dot{\alpha}/K_{sv}+\alpha/K_{sv} \tag{10}$$

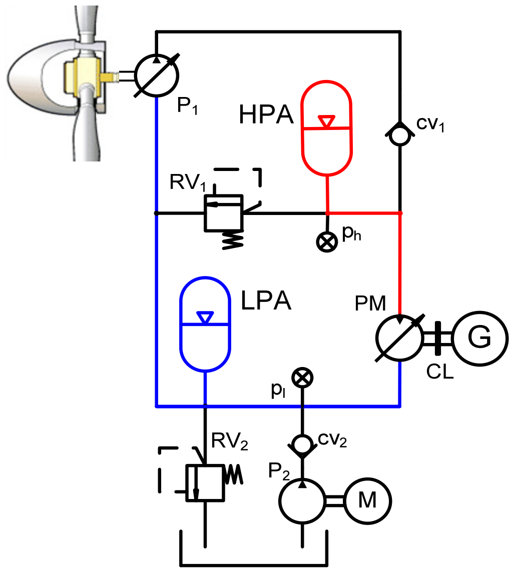


Fig. 2 Hydraulic circuit of SCHST-WECS

3.4 Model and calculation of hydraulic accumulator

High-pressure accumulator plays an important role in the SCHST-WECS. Its volume must be significantly large to absorb almost energy from turbine and compensate power to drive the hydraulic motor during the shortage wind power. In the proposed system, we employed a bladder accumulator, which filled with nitrogen gas. According to Rabie [19], the nitrogen gas is assumed to compress and expand based on the adiabatic gas law:

$$pV^n = p_0V_0^n = p_{\max}V_{\min}^n \tag{11}$$

Then the fluid volume in the hydraulic accumulator HPA is derived as:

$$V_f = \begin{cases} 0, & if\ p_i \le p_0 \\ V_0\left(1-p_0/p_i\right)^{1/n}, & else \end{cases} \tag{12}$$

The energy that can be absorbed by HPA is calculated as:

$$E = V_0 p_0^{1/n}\left[p_{\max}^{(n-1)/n} - p_0^{(n-1)/n}\right]/(n-1) \tag{13}$$

The optimal pre-charged pressure for maximum energy capacity of HPA is given by:

$$p_0 = n^{n/(1-n)}p_{\max} \tag{14}$$

And the maximum energy stored in HPA is given by:

$$E_{\max} = p_{\max}V_0/n^{n/(n-1)} \tag{15}$$

Then the volume of HPA is derived as:

$$V_0 = E_{w,\max}n^{n/(n-1)}/p_{\max} \tag{16}$$

3.5 Model of connecting line

The pressure in high pressure line p_h is expressed as:

$$\frac{dp_h}{dt} = \left(Q_{po} - Q_{ha} - Q_r - Q_{pm}\right)\beta/V_h \tag{17}$$

Q_{po}- is output flow rate of the pump P_1 expressed by:

$$Q_{po} = \begin{cases} \omega_p D_{max}\alpha - Q_{pl}, & if\ p_h \le p_{set} \\ 0, & else \end{cases} \tag{18}$$

Q_{ha} is the flow rate into HPA, from (12), Q_{ha} was calculated as:

$$Q_{ha} = \begin{cases} 0, & if\ p_i \le p_0 \\ \frac{d}{dx}\left[V_0\left(1-p_0/p_i\right)^{1/n}\right], & else \end{cases} \tag{19}$$

Q_{pi} is the actual flow rate into the inlet port of the pump expressed in (4),

Q_r is the flow rates via the relief valves RV_1, expressed by (20):

$$Q_r = \begin{cases} 0, & if\ \Delta p \le p_{set} \\ C_d A_v \sqrt{2\Delta p / \rho}, & if\ \Delta p \ge p_{set} \end{cases} \quad (20)$$

$$\Delta p = p_h - p_l \quad (21)$$

3.6 Model of load

The generator causes the load on motor M. The dynamic equation of the load is obtained by applying Newton's second law, as:

$$T_m = J\dot{\omega} + C\omega + T_r \quad (22)$$

where, T_m is the torque generated by the hydraulic motor, presented in (9); J, C and ω are inertial moment, viscous friction coefficient and the speed of the generator, respectively; T_r is the rated torque to create the electric current.

4. Simulation

Based on the parameters of the generator and wind speed, hydraulic components of the proposed system could be calculated and chosen as shown in Table 1.

Table 1 Setting parameters of the system

Components	Capacity	Unit
Hyd. Pump P_1		
Displacement	1000	cc/rev
Max pressure	250	bar
Hyd. Motor PM		
Displacement	55	cc/rev
Max pressure	250	bar
HPA		
Volume	80	L
Gas pre-charge	150	bar
Max pressure	280	bar
LPA		
Volume	100	L
Gas pre-charge	2	bar
Generator		
Rated power	15	kW
Rated speed	1500	rpm
Pole number	4	poles

To assess the performance of the SCHST-WECS, three simulations were carried out. Simulation 1 describes the variation of wind power and the performance of the SCHST-WECS. Simulation 2 was done with the same parameters as simulation 1 but with the conventional hydrostatic transmission WECS without accumulator. Simulation 3 verified the effectiveness of the proposed system.

Simulation 1

The results of Simulation 1 were shown in Fig. 3, 4 and 5. Figure 3 presents the speed response of the hydraulic motor PM in the case wind power varies in a wide range. The speed of the turbine is simulated by a sinusoidal function. The turbine speed, also means speed of the hydraulic pump P_1, varies from zero to 90rpm. The reference speed is switched to 1500rpm only when the pressure of the accumulator HPA reaches 240bar, and it is quickly reduced to zero when the pressure decreases of 160bar, as shown in Fig. 4. The flow rate the accumulator HPA and the relief valve RLV_1 are also shown in Fig. 4. The positive flow rate of the accumulator HPA means the input flow rate, and vice versa. The relief valve is set at 300bar to protect the hydraulic circuit. When the pressure of the accumulator HPA reaches 300bar, there is no more fluid entering it. The fluid in the high-pressure line is let out to the low pressure line via the relief valve RLV_1. The gas volume in the accumulator HPA vibrates contrarily to its pressure.

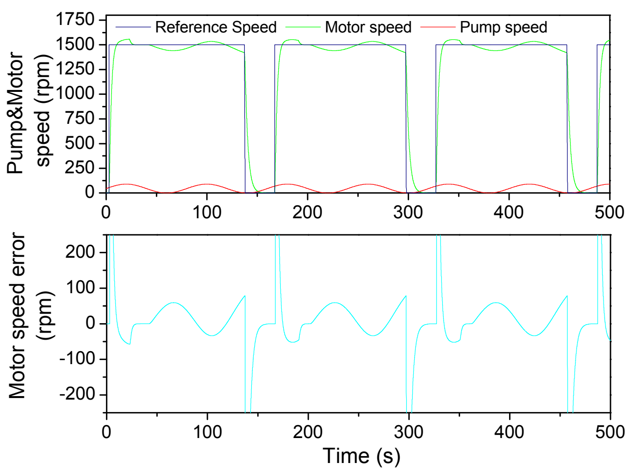


Fig. 3 Speed responses of the hydraulic motor 4 in the 1st simulation

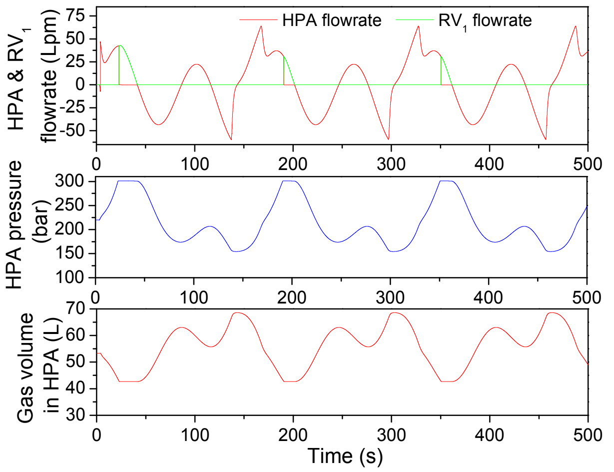


Fig. 4 Flow rate, pressure, gas volume of the hydraulic motor PM and flow rate of the relief valve RL_1 in the 1st simulation

Figure 5 illustrates the power and energy absorbed by the pump P1 and generated by the motor PM. Although the input power widely varies from zero to 46 kW, the output power is maintained about 15kW. At the end of the simulation, the input energy is 8895kJ while the output energy is 5966kJ.

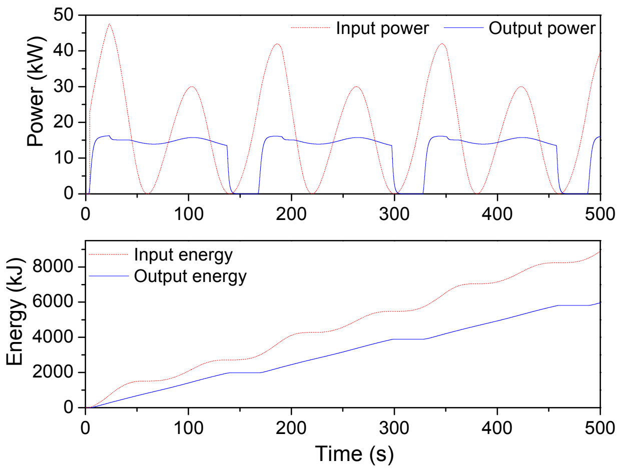
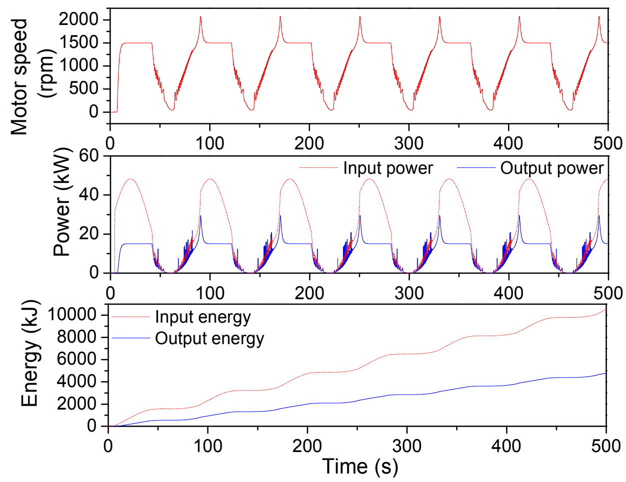


Fig. 5 Input/output power and energy of SCHST-WECS in the first simulation

Simulation 2

Figure 6 shows the Motor speed, Input/output Power and Energy of HST-WECS with the same parameters as the first simulation but without accumulator. The motor speed is difficult to control, the output power is variable in wide range and output energy is lower than the case with the accumulator.



Simulation 3

The simulation 3 is done to evaluate the efficiency of the SCHST-WECS, as shown in Fig. 7, 8 and 9. The turbine speed is also simulated by a sinusoidal function, but varies in a narrower range from 20 to 70rpm to make sure that overpressure does not occur. The speed response is shown in Fig. 7: the maximum speed error is 25rpm or less than 2%. The pressure in the accumulator HPA fluctuates under 300bar and no fluid flows through the relief valve RLV1, as shown in Fig. 8. The input power to the pump P1 varies 10 to 32kW whereas the output power from the motor PM oscillates lightly around 15kW as shown in Fig. 9. At the end of the simulation, the input energy is 10339kJ while the output energy is 7283 kJ. Then the efficiency of the proposed system is calculated as 70.4%.

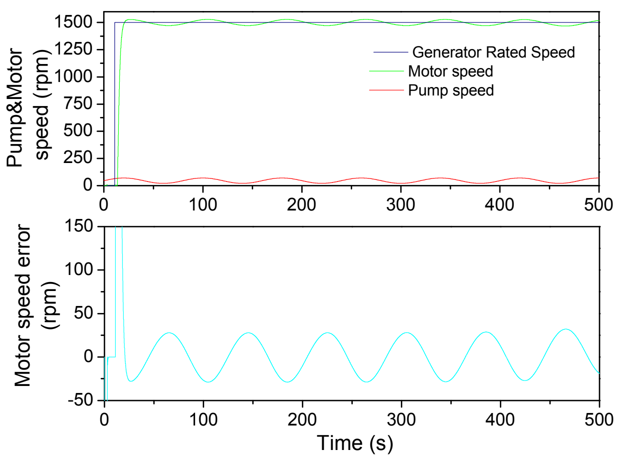


Fig. 7 Speed response of the hydraulic motor in the third simulation

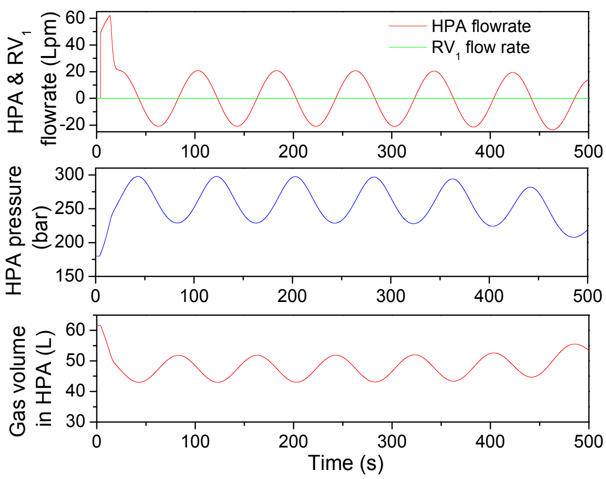


Fig. 8 Flow rate, pressure, gas volume of the hydraulic accumulator HPA and flow rate of the relief valve RLV1in the third simulation

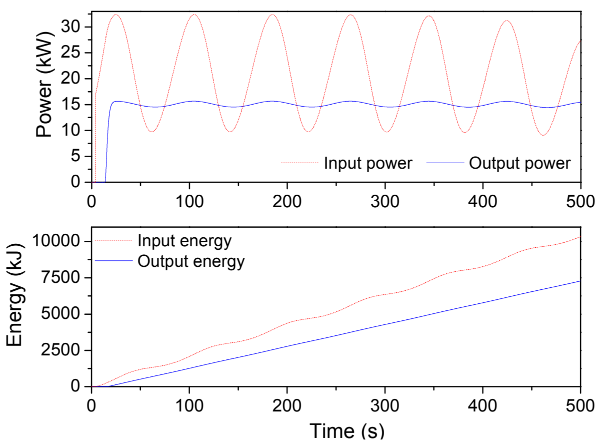


Fig. 9 Input/output power and energy of SCHST-WECS in the third simulation

5. Conclusion

A Secondary Control Hydrostatic Transmission for Wind Energy Conversion System was developed in this study. Mathematical model of hydraulic components was presented to establish the simulation program by using AMESim software. All parameters for the simulation were based on real components.

Simulation was carried out in the condition of speed variation and disturbance load to evaluate the efficaciousness of the proposed system.

Simulation results indicated the wind energy absorbability and transmutability of SCHST-WECS as well as good performance in maintenance the output speed to satisfy the operating conditions of the generator. SCHST-WECS could salvage the excessive power to increase the efficiency. The speed relative error was less than 2%; the efficiency of SCHST-WECS was 70.4%.

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